

Exotic charmonium spectroscopy with CMS

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The latest results of CMS in the area of exotic quarkonium decays will be presented: observation of a peaking structure in $J/\psi\phi$ mass spectrum in the decay $B^\pm \rightarrow J/\psi\phi K^\pm$, search for new bottomonium states in $\Upsilon(1S)\pi^+\pi^-$ mass spectrum, measurement of prompt J/ψ pair production.

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1 Introduction

The first, unexpected, charmonium state to be seen was the $X(3872)$, observed by Belle in 2003, in the decay $B^+ \rightarrow J/\psi K^+ \pi^+ \pi^-$ [1]. Several other states have been discovered since then, but their nature is not yet well understood. Several interpretations do exist, they can be tetraquarks, or hadronic molecules or hybrid mesons with a gluon content [2]. Their bottomonium partners are also looked for.

2 Data samples and selections

The results obtained from the analysis of data collected by CMS in 2011 at $\sqrt{s} = 7$ TeV, corresponding to an integrated luminosity $\mathcal{L} \sim 5 \text{ fb}^{-1}$, and in 2012 at $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity $\mathcal{L} \sim 20 \text{ fb}^{-1}$, will be shown in the following.

Dedicated triggers have been developed for the analyses to achieve a sustainable trigger rate when collecting data at the very high luminosities provided by LHC. The presence of two muons was required, with an invariant mass compatible with a J/ψ or an Υ , forming a secondary vertex displaced from the primary interaction point and a momentum direction compatible with the flight direction.

3 Peaking structure in $B^\pm \rightarrow J/\psi \phi K^\pm$

The $Y(4140)$ was first observed by CDF [3], with a mass near the $J/\psi \phi$ threshold and a narrow width: $\Gamma = (11.7_{-5.0}^{+8.3} \pm 3.7) \text{ MeV}$. A consistent mass peak has been observed by D0 [4], but has not been confirmed by Belle [5] and there's no evidence from LHCb [6]. Its mass is well above the threshold for open charm decay, and probably it's not a P -wave charmonium. Possible interpretations of its nature are a $D_s^* \bar{D}_s^*$ molecule with $J^{PC} = 0^{++}$ or $J^{PC} = 2^{++}$, or an hybrid charmonium with $J^{PC} = 1^{-+}$; the hypothesis of a $c\bar{c}s\bar{s}$ tetraquark is compatible with $J^{PC} = 1^{++}$ but not $J^{PC} = 0^{++}$ [7].

CMS reconstructed this state [8] combining J/ψ candidates with 3 charged tracks with total charge ± 1 and consistent with originating from the J/ψ vertex; a $K^+ K^-$ pair with an invariant mass compatible with the ϕ was then looked for. Invariant mass distributions for the ϕ and the B^+ candidates are shown in fig.1.

The $J/\psi \phi$ mass distribution is populated by a large combinatorial background, so the search is performed looking at the distribution of the mass difference $\Delta m \equiv m(\mu^+ \mu^- K^+ K^-) - m(\mu^+ \mu^-)$. Candidates have been divided into 20 MeV wide Δm intervals, and for each interval the yield has been extracted fitting the total $J/\psi \phi K$ mass distribution. The signal has been fitted with two gaussians with mean fixed to B^+ mass and the background has been fitted with a second order polynomial. An

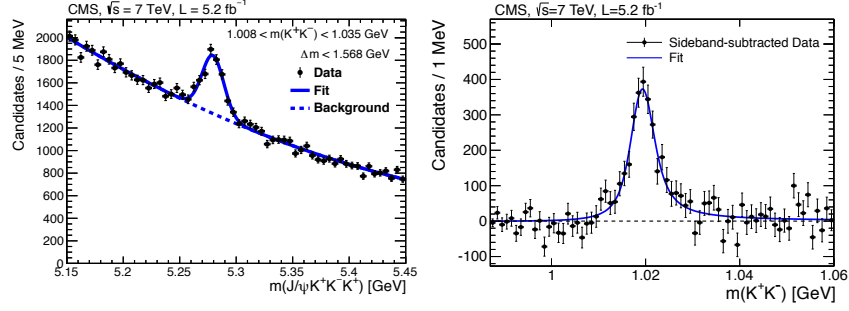


Figure 1: Invariant mass distribution for the $J/\psi\phi K^+$ (left) and the K^+K^- (right). K^+K^- mass distribution has been obtained from candidates within $\pm 3\sigma$ of the nominal B^+ mass and performing a sideband subtraction.

unbinned maximum likelihood fit has been performed simultaneously for all intervals and the results are shown in fig.2.

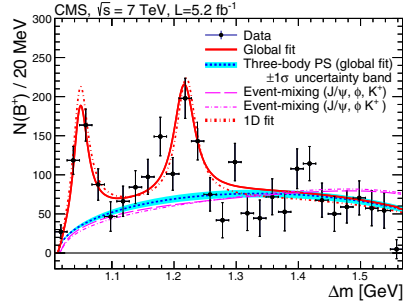


Figure 2: Number of $B^\pm \rightarrow J/\psi\phi K^\pm$ candidates as a function of Δm . The results of several fit procedures are shown [8].

The distribution of Δm was then corrected for the detection and reconstruction efficiency, that was estimated with simulation. Different assumptions have been used for the polarization, and a negligible effect has been observed. The searched state has unknown quantum numbers, so different assumptions have been considered for the J/ψ helicity angle distribution, and a 10% effect was observed and included in the systematic uncertainty.

Checks have been performed to test the possibility that the observed peaks are actually reflections of resonances on the other 2-body systems, ϕK or $J/\psi K$. Several resonances with various masses, widths and helicity angle distributions have been simulated, but none of them reproduced the observed spectrum. As an additional check, the mass distribution of the 3 kaons has been investigated (fig.3), and an excess in the region $1.7 \div 1.8$ GeV is observed; the peaks are still visible also when the excess region is removed.

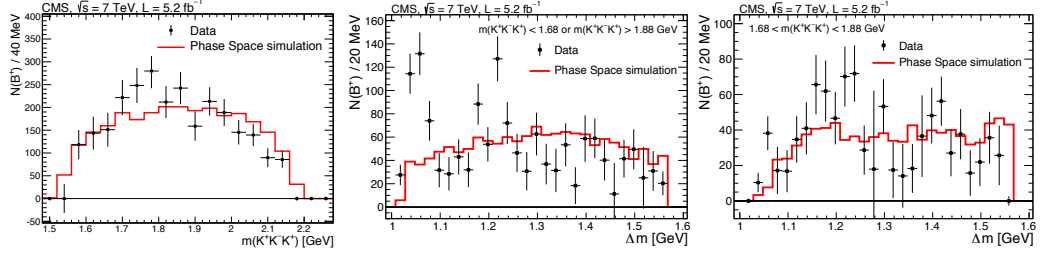


Figure 3: Yield of $B^+ \rightarrow J/\psi K^+ K^- K^+$ candidates as a function of the $K^+ K^- K^+$ invariant mass (left) and number of $B^\pm \rightarrow J/\psi \phi K^\pm$ candidates as a function of Δm requiring $m(\phi K)$ outside (middle) or inside $[1.68, 1.88]$ GeV range (right).

The analysis was also restricted to the region with $m(\phi K) > 1.9$ GeV to remove possible effect from the $K_2(1770)$ and $K_2(1820)$ resonances, and the structure was still visible. To compute systematic uncertainties and perform final cross checks different fit procedures and background estimations have been tried. The fit results for mass and width of the two peaks are reported in table 1.

	yield	Δm (MeV)	m (MeV)	Γ (MeV)
low	310 ± 70	1051.3 ± 2.4	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$
high	418 ± 170	1217.1 ± 5.3	$4313.8 \pm 5.3 \pm 7.3$	$38^{+30}_{-15} \pm 16$

Table 1: Fit results for mass and width of the two peaks; m_1 and m_2 values have been obtained adding the J/ψ mass to the corresponding Δm .

4 Search for a new bottomonium state decaying to $\Upsilon(1S)\pi^+\pi^-$

The search for a bottomonium partner of $X(3872)$ has been conducted; such a state is predicted both by tetraquark model and hadronic molecular calculations; several mass predictions do exist, but a mass difference between the X_b and the Υ larger than 1 GeV is predicted by all models. There are anyway important differences when comparing the decay $X_b \rightarrow \Upsilon(1S)\pi^+\pi^-$ with the decay of $X(3872) \rightarrow J/\psi\pi^+\pi^-$, leading to a smaller isospin violation in X_b decay than in $X(3872)$ [9].

CMS looked for this state [10] in events with a $\Upsilon(1S)$ candidate and 2 additional opposite-charged tracks, assumed to be pions. A common vertex has been fitted with muons and pions, and the invariant mass has been computed by constraining the dimuon mass to the $\Upsilon(1S)$. The mass distributions are shown in fig.4, for rapidity

intervals in the barrel and endcap regions, and the two peaks corresponding to $\Upsilon(2S)$ and $\Upsilon(3S)$ are visible.

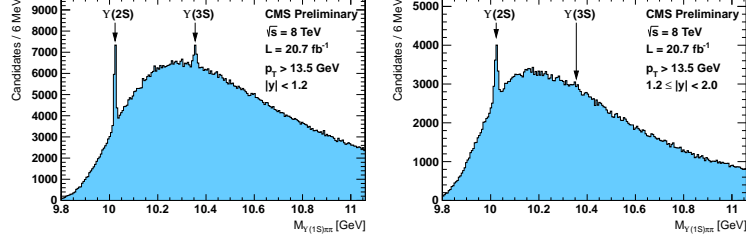


Figure 4: Reconstructed invariant-mass distributions of the candidates in the barrel (left) and endcap (right) regions.

The search has been performed estimating, for different hypotheses for the X_b mass, the ratio R of cross-sections for X_b and $\Upsilon(2S)$:

$$R = \frac{\sigma(pp \rightarrow X_b \rightarrow \Upsilon(1S)\pi^+\pi^-)}{\sigma(pp \rightarrow \Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-)}.$$

The search has been performed in two mass regions, $[10.06, 10.31]$ GeV and $[10.40, 10.99]$ GeV, to exclude the $\Upsilon(2S)$ and $\Upsilon(3S)$; the mass spectrum has been fitted with a gaussian function for the resonances and a polynomial for background. The X_b mass has been shifted by 10 MeV steps, while its width has been assumed to be small, and the resolution was taken from simulation. The ratio R was then given by the ratio of the observed candidates scaled with the ratio of efficiencies. Signal strength, P -values and cross section limits have been computed versus the X_b mass. Results are shown in fig.5.

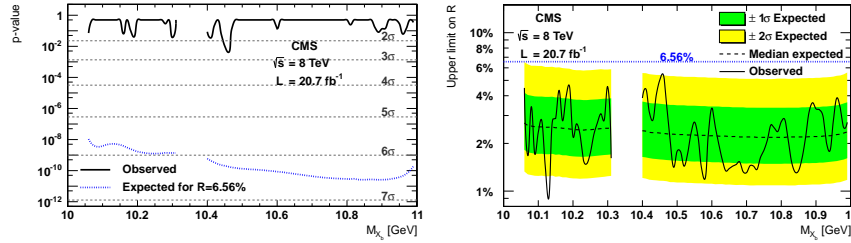


Figure 5: P -value (left) and upper limit at 95% confidence level on R (right) as a function of the assumed X_b mass. The lines at 6.56% correspond to the expectations for the analogous $X(3872)$ decay to $J/\psi\pi^+\pi^-$.

Systematic uncertainties have been estimated by considering different models for dipion mass distribution and varying the efficiency dependence on X_b mass. Different models for the mass distributions and resolutions have been considered as well as different assumptions for X_b polarization.

5 Measurement of prompt J/ψ pair production

In proton-proton collisions at LHC energies the very high parton density make possible having multiple parton scattering; single parton scattering is anyway assumed to dominate. The production of two J/ψ is possible also in single parton scattering, but a pair of strongly correlated J/ψ is expected, with a small rapidity difference $|\Delta y|$. Double parton scattering on the contrary allows multiple heavy-flavour production with large $|\Delta y|$ [11]. The production of J/ψ pairs may undergo through the production of a color singlet, that is dominant at low transverse momenta, or through the production of a color octet turning into a singlet with the emission of a gluon, that becomes important at high p_T [12]. J/ψ pairs can also be produced in the decay of η_b , but this decay is expected to be suppressed by non relativistic QCD [13]; other sources could be exotic states as tetraquarks [14].

At CMS the differential cross-section was measured [15] versus 3 variables: the invariant mass $m_{J/\psi J/\psi}$ of the J/ψ pair, the rapidity difference $|\Delta y|$ and the transverse total momentum $p_{T,J/\psi J/\psi}$. The differential cross-section is computed as

$$\frac{d\sigma(pp \rightarrow J/\psi J/\psi + X)}{dx} = \sum_i \frac{s_i}{a_i \cdot \epsilon_i \cdot (\mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-))^2 \cdot \Delta x \cdot \mathcal{L}}$$

The sum is performed over all events i in an interval Δx : x is one of the 3 kinematical variables listed above, s_i is the probability of the event to be signal, a_i and ϵ_i are the acceptance and the detection efficiency, \mathcal{L} is the integrated luminosity and \mathcal{B} is the branching ratio for the J/ψ to decay into two muons.

Events have been selected requiring at trigger level at least 3 muons with different charge, and at reconstruction 4 muons with at least 3 of them matching the trigger; kinematic cuts are applied to transverse momenta, pseudorapidity of the single muons and rapidity of the J/ψ candidates. Additional selections are applied cutting on the “proper transverse decay length” $ct_{xy} = (m_{J/\psi}/p_{T,J/\psi}) \cdot L_{xy}$ and the ratio of the distance between the dimuon vertices $|\Delta \vec{r}|$ and its error $\sigma_{|\Delta \vec{r}|}$. Acceptance have been computed event by event generating a large number of events starting from measured J/ψ 4-momenta and dividing the number of events surviving the acceptance cuts by the number of trials.

The signal weights are obtained by a maximum likelihood fit of the distributions of the invariant masses of the two J/ψ , the proper transverse decay length of the highest- p_T J/ψ and the distance significance. In the fit five categories have been considered: prompt J/ψ pairs, that’s the signal, events with at least one non-prompt J/ψ , events with one J/ψ and a combinatorial dimuon, and events with two combinatorial dimuons.

The differential cross-section versus $m_{J/\psi J/\psi}$, $|\Delta y|$ and $p_{T,J/\psi J/\psi}$ is shown in fig.6; the total cross section is

$$\sigma(pp \rightarrow J/\psi J/\psi X) = (1.49 \pm 0.07 \pm 0.14) \text{ nb}$$

Looking at the η_b mass region no excess is seen; the enhancement at large rapidity difference shows a hint of double parton scattering.

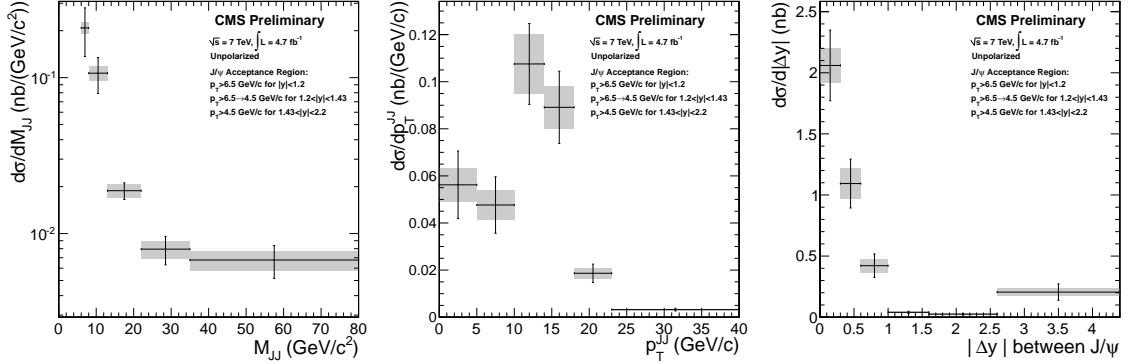


Figure 6: Differential cross-section for the production of a prompt J/ψ pair versus the invariant mass $m_{J/\psi J/\psi}$ of the J/ψ pair (left), the rapidity difference $|\Delta y|$ (middle) and the transverse total momentum $p_{T,J/\psi J/\psi}$ (right).

6 Conclusions

A structure has been observed in $J/\psi\phi$ mass in $B^\pm \rightarrow J/\psi\phi K^\pm$ decays, showing two peaks at masses 4148 GeV and 4313 GeV.

A search has been conducted for a bottomonium partner of $X(3872)$ and a limit on the production of cross-section times the branching ratio to $\Upsilon(1S)\pi^+\pi^-$ has been set.

A measurement of the cross-section for the production of a prompt J/ψ pair has been performed, and hints for double parton scattering have been observed, while no evidence appeared of $\eta_b \rightarrow J/\psi J/\psi$ decay.

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